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Abstract

Intensifying land use is often seen as a corollary of improving rural livelihoods in developing countries. However, land use intensification (LUI) frequently has unintended impacts on ecosystem services (ES), which may undermine the livelihoods of the same people who could benefit from intensification. Poorer households are disproportionately dependent on ES, so inequalities may also rise. A disaggregated analysis of LUI is thus fundamental to better understand how LUI can progress in an equitable manner. Using a suite of multi-scale, multidisciplinary social-ecological methods and operationalising multidimensional concepts of land use intensity and wellbeing, we examine three case studies in rural Mozambique. Drawing on qualitative focus group discussions, 1576 household surveys and geospatial data from 27 Mozambican villages, we assess how wellbeing and inequality change with three common LUI pathways: transitions to smallholder commercial crop production, charcoal production, and subsistence expansion. Wellbeing improved with intensification of smallholder commercial and subsistence agriculture, inequality did not change. Intensification of unsustainable charcoal production showed no overall effect on either wellbeing or inequality. Improvements in wellbeing amongst the poorest households were only found with intensification of commercial crop production where villages had highly accessible markets. Our findings suggest that socioeconomic benefits from agricultural intensification and expansion may overcome localised environmental trade-offs, at least in the short term. However, unsustainable charcoal resource management and limited productive investment opportunities for rural households resulted in both reduced market access and limited wellbeing improvements. Sustainable and inclusive markets are therefore crucial developments alongside LUI to sustain wellbeing improvements for all households, to ensure that no one is left behind.

Keywords:

Sustainable Development; Livelihoods; Human Wellbeing; Poverty; Land Use Intensification; Ecosystem Services

1. Introduction

Growing global demand for food, fibre, fuel and economic globalization are increasing pressures on arable land and remaining forests (Lambin and Meyfroidt, 2010). Consequently, land use is set to intensify in sub-Saharan Africa (SSA) alongside increasing rural population pressures and competition from national and global investors (Jayne et al., 2014). However, much of the remaining available land is concentrated within a few countries (Chamberlin et al., 2014). Simultaneously, poverty analysts emphasise the value of access to productive assets, such as land, through which people can create routes out of poverty (Ellis and Freeman, 2004). When households have access to land resources, land use intensification (LUI) may therefore provide routes out of poverty (Jayne et al., 2003; Shackleton et al., 2007). Accordingly, intensifying land use is a consequence of global and regional economic development and of particular importance to rural livelihoods.

It is widely held that reducing poverty in SSA will rely largely on stimulating agricultural growth (The World Bank, 2009), thus cropland expansion is expected to be necessary for smallholder-led development across the region (Chamberlin et al., 2014; Jayne et al., 2014). Yet, conversion of land for agriculture is the leading cause of deforestation in SSA (Gibbs et al., 2010; Hosonuma et al., 2012; Rudel et al., 2013). In parallel, biomass energy (particularly of charcoal and firewood) is the most important fuel source for SSA, its consumption has been shown to play a critical role in economic growth for the region (Ozturk and Bilgili, 2015). By 2030, over 12 million people will be involved in SSA's charcoal sector (Mwampamba et al., 2013). However, 80% of global charcoal-based tropical deforestation occurs in Africa (Chidumayo and Gumbo, 2013).

Improvements in rural livelihoods are often an implicit assumption with LUI (Liao and Brown, 2018). Despite some evidence for observed beneficial wellbeing outcomes of smallholder intensification pathways, particularly of those deemed sustainable (Asfaw et al., 2012; Pauw and Thurlow, 2011; Rist et al., 2010; Shively and Pagiola, 2004), there are concerns that associated negative environmental impacts (de Vries et al., 2013; Flynn et al., 2009) undermine rural livelihoods (Rasmussen et al., 2018; Woollen et al., 2016). Across much of SSA, many rural households are inextricably dependent on woodland and forest-derived ecosystem services (ES) (Ryan et al., 2016; Shackleton et al., 2007). Furthermore, as the poorest are disproportionately dependent on natural resources (Angelsen et al., 2014; Makoudjou et al., 2017), there is potential to exacerbate rural inequalities. Understanding how human wellbeing changes with LUI is therefore key in the pursuit of global development, especially as ES underpin many of the UN Sustainable Development Goals (SDGs) (Wood et al., 2018). Furthermore, with the imperative of the SDGs to 'leave no one behind', a disaggregated analysis of LUI is critical (Milder et al., 2014) as it is fundamental in identifying the most vulnerable groups, to recognise how they use, access and depend upon resources (Daw et al., 2011; Dawson and Martin, 2015; Fisher et al., 2013).

Much research on LUI tends to focus on the environmental impacts (Foley, 2005), particularly of agricultural intensification and expansion (Allan et al., 2015; Matson et al., 1997; Power, 2010; Tscharntke et al., 2005). Few examinations of the livelihood impacts mostly assess the extent of a particular land cover (e.g. swidden agriculture) or of unidimensional intensification indicators, such as agricultural yields or fertiliser application rates (van Vliet et al., 2012). Yet, LUI is a complex process that incorporates multiple dimensions embedded within complex socio-ecological systems and landscapes. Furthermore, land use impacts have rarely been traced through to livelihood and wellbeing outcomes, or to an examination of the net multidimensional and social-ecological outcomes (Rasmussen et al., 2018). Understanding the outcomes of LUI on both the environment and people must take a replicable and dynamic multidimensional approach, applicable to the landscape scale. One such approach is Erb et al's., (2013) conceptual framework for LUI, where LUI is a combined process of inputs to a production system (e.g. of land, labour or technology), outputs from the production system (e.g. products and services) and modifications to system properties and functions (e.g. to soil quality, biodiversity and carbon stocks and flows). The framework puts the production system at the centre and embedded within a given landscape, making the framework applicable at the system level, and uses indicators of intensification for all three dimensions. Importantly, under this framework, LUI is the intensification of any land use, including forestry, inland fisheries, urban areas and agriculture (both crop and livestock), and thus may also result in changing land use, for example from forestry to agriculture, or a shift from subsistence agriculture to commercial agriculture. With this definition, and somewhat counter-intuitively, LUI can involve inputs of land, thus agricultural expansion is a form of LUI. See SI.1 for a schematics of Erb et al's., (2013) LUI framework, and for further explanation of intensification agricultural production systems, under this framing of LUI.

The impacts of LUI on rural livelihoods are not fully understood (van Vliet et al., 2012), yet understanding how livelihoods change with LUI is critical as changes in land and land use have reflexive implications for livelihood outcomes (Carr and McCusker, 2009). Market factors also have implications for both LUI and livelihoods, as the development of market opportunities is a main driver of LUI (van Vliet et al., 2012). Markets stimulate livelihood diversification, particularly growth into non-farm sectors (Haggblade et al., 2010), thus people's ability to escape poverty is diminished by poorly functioning markets (Ellis and Freeman, 2004). Equally, poor market access hampers LUI (Bamire and Manyong, 2003; Woodhouse, 2002), whereas improved access stimulates and intensifies commercial forest product extraction (Robinson et al., 2002) and cropland expansion (Hertel et al., 2014). However, whilst markets can increase local incomes, this can result in trade-offs with human, environmental and social capitals (van Vliet et al., 2012). LUI and markets thus have significant, but poorly understood consequences for rural populations. A clearer understanding of how LUI may proceed in a more equitable manner is required, so that no one is left behind.

There are calls for research to examine multiple land uses (Fischer et al., 2014) and to use a unified, systematic, and multidimensional approach to measure LUI (Erb et al., 2013). In this paper, we apply the integrative LUI conceptual framework, as defined by Erb et al., (2013), to define and measure LUI using locally relevant indicators. Mozambique retains surplus land (Chamberlin et al., 2014; Lambin and Meyfroidt, 2011) available for intensification and thus offers the opportunity to examine how multidimensional wellbeing (MDWB) and associated inequalities change with intensification of three of the most prevalent LUI pathways occurring in SSA, under conditions of relative land abundance: smallholder subsistence expansion, transitions from smallholder subsistence to commercial crop production, and charcoal production. Using three case-study LUI pathways in Mozambique, we reflect on the smallholder-dominated landscapes of rural SSA, to contribute new insights to current understandings of LUI. The objectives of this study are as follows:

- Adapt and apply Erb et al's., (2013) conceptual framework to empirically measure three multidimensional case-study LUI pathways
- Explore the relationship between three prevalent LUI pathways and measures of MDWB
- Examine the implications of market access on LUI and MDWB

2. Methods

2.1. Study sites

2.1.1. Land use history in Mozambique

Mozambique has a unique land use and land tenure history, largely shaped by colonial rule, civil conflict and resolution, and more recent emergence of forced displacement from large-scale land acquisitions. With independence from Portugal in 1975, large colonial-run farms were abandoned and subsequently converted into state-run enterprises, following socialist development ideology (Zaehringer et al., 2018). During the Civil War (1977-1992), State enterprises were discontinued and many rural households abandoned rural areas (Unruh, 1998); the civil war reduced the amount of land under agricultural production, largely confining agricultural areas to urban peripheries (Temudo and Silva, 2011). Post-war, farming lands were reoccupied by internally displaced populations; despite repopulation of rural areas, Mozambique is currently considered land abundant (Chamberlin et al., 2014; Lambin and Meyfroidt, 2011). The 1990 Constitution defines land as state property, allowing only use rights to individuals (Brück and Schindler, 2009). Following post-war agricultural reforms promoting a liberalised market economy, sector development has emphasised investment for large-scale agricultural operations and encouraged foreign companies to acquire secure land rights, known as *Direito de Uso e Aproveitamento da Terra* (DUAT) (German et al., 2016). According to the Mozambican Land Law (Government of Mozambique, 1997), land use rights can be allocated providing no prior usage or if the requester can prove their use for at prior ten years. However, recent land conflicts have emerged whereby companies have obtained land rights from often-inhabited areas, leading to land and resource conflicts (Bleyer et al., 2016; Zaehringer et al., 2018). The Mozambican Land Law (Government of Mozambique, 1997) has legal procedures whereby farmers must be compensated by means of an agreed payment or relocation. For example, the “Regulamento sobre o Processo de Reassentamento” (Decree no. 31/2012) states that the quality of life has to be maintained or improved when resettlement takes place (Government of Mozambique, 2017). The National Land Policy also has a specific objective for ‘promotion of private investment in ways that do not harm local interests’, though there are no clear mechanisms to achieve this (German et al., 2016). However, in practice outcomes are largely unsatisfactory (Kaarhus, 2018; Vermeulen and Cotula, 2010).

2.1.2. Contemporary land use histories across the study sites

For this study, twenty-seven villages were studied in Gurué (n=10), Mabalane (n=7) and Marrupa (n=10) Districts, in Mozambique (Fig. 1). Gurué District, in Zambezia Province, is one of the main commercial crop producing regions in Mozambique and smallholder commercial agriculture is a dominant production mode in the region; the most important commercial crops are soya, pulses, sunflower and sesame (Government of Mozambique, 2010), which are mostly grown for the export market. More than 90% of the District's agricultural land is cultivated by smallholders (estimated holding size of 1.5-2.5 hectares), using few or no exogenous technological inputs. Almost 7% of the region's agricultural area is leased by the private sector (Government of Mozambique, 2015), giving rise to increasing land conflicts between local smallholders and large-scale commercial operators (Zaehringer et al., 2018).

Mabalane District, in Gaza Province, is currently the major charcoal production area supplying Maputo city, where charcoal is the dominant source of domestic urban energy. Rural production is dominated by non-local, large-scale operators who typically employ migrant producers and retain 92% of profits (Baumert et al., 2016). Charcoal production is also a dominant income generating strategy for rural households in Mabalane, whereby local households engage in small-scale charcoal production, producing fewer than 100 sacks per month (ibid). Following a von-Thunen pattern of forest extraction (Ahrends et al., 2010), the area of land used for charcoal production in Mabalane has grown with increasing distance from Maputo city (Luz et al., 2015).

In Marrupa District, Niassa Province, sparse population densities, isolation from the rest of the country, and a lack of basic infrastructure have led to historically underdeveloped commercial markets (agricultural, forest or otherwise) (ORGUT Consulting, 2016; Temudo and Silva, 2011). Some cash crop production exists in the region (e.g. tobacco), and households sell surplus agricultural produce. The dominant land-use pressure in the study site originates from population growth, driving the expansion of subsistence cultivation, as opposed to agricultural expansion for cash crops (Temudo and Silva, 2011). Smallholder (< 5 ha) low-input rain-fed subsistence cultivation systems, with long fallow cycles, is the dominant land use, where maize is the staple crop (Åkesson et al., 2009; ORGUT Consulting, 2016; Temudo and Silva, 2011). Given the low population densities in the region, land scarcity does not generally exist, although private investments are seen to be increasing local land conflicts (Künnemann and Monsalve Suárez, 2013; Matavel et al., 2011; Mousseau and Mittal, 2011).

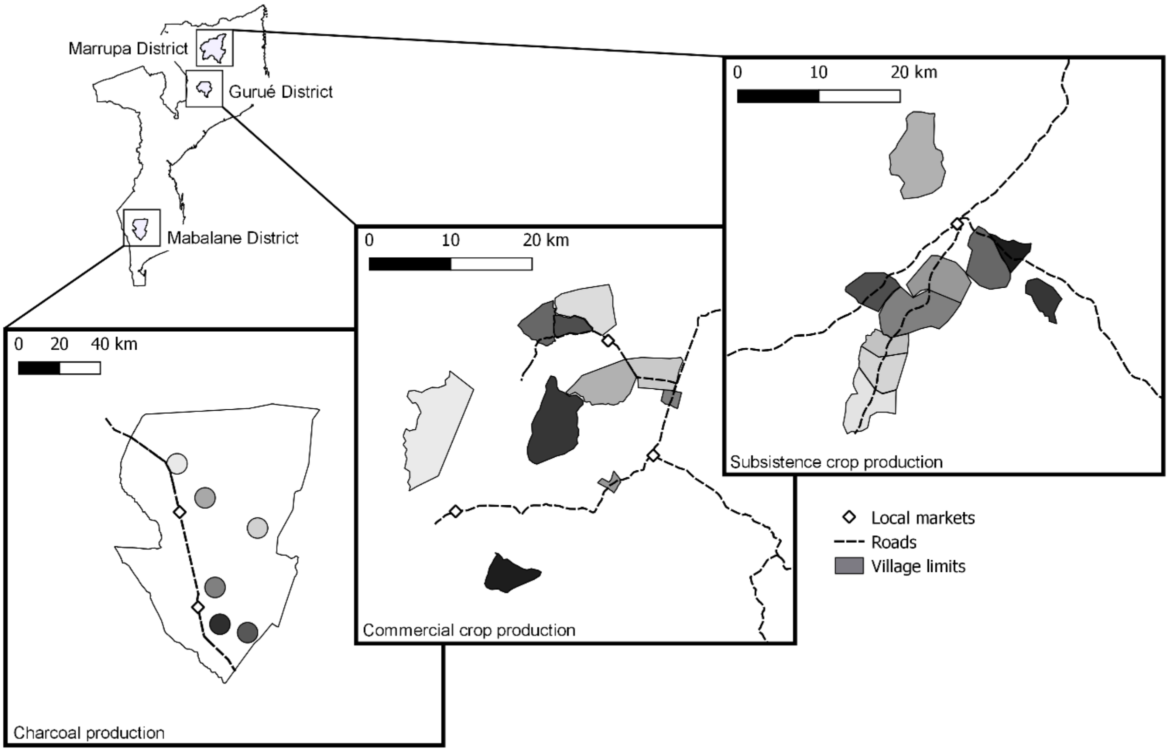

Fig. 1: Village locations in each case study site and spatial patterns of land use intensification gradients: Charcoal production in Mabalane District; Smallholder commercial crop production in Gurué District; Subsistence crop production in Marrupa District. Darker shades of grey indicate villages with higher levels of land use intensification (see results section 3.1), lighter shades of grey indicate villages with lower levels of land use intensification.

2.2. Data collection

Between 2014 and 2015, quantitative and qualitative social and geospatial data were collected from the 27 studied villages: Mabalane was sampled during May-October 2014; Marrupa May-August 2015; Gurué August-December 2015. Villages had similar vegetation types, infrastructure, climatic conditions and dominant land use activities, relative to each case-study site in which they were located (Baumert et al., 2016; Luz et al., 2015; Mahamane et al., 2017; Smith et al., 2019; Vollmer et al., 2017; Woollen et al., 2016; Zorrilla-Miras et al., 2018). We based village selection on stringent criteria to ensure comparability between villages (e.g. similar baselines), to enhance the validity of the LUI chronosequence (see SI.2 for village selection criteria).

The aim of the village sample was to choose villages with comparable infrastructure in each site, to enable comparisons between villages. However, post sampling we found an anomaly village in Marrupa that had year-round access to improved water, and consequently the MDWB indictor for this one village was substantially higher. As such, in our results we present the results of the nine comparable villages. See SI.5 for a table of the village-level wellbeing data and LUI indices.

2.2.1. Social data

A household list was compiled in each village, whereby households were defined as people 'eating from the same pot'. We conducted participatory wealth rankings with key informants. Information from the participatory wealth rankings were used to identify local indicators of wealth and wellbeing (Chambers, 1994) and the wealth rankings were used to select participants for the household survey, using a stratified random sampling approach (Laws et al., 2013). Household surveys (n=1576) were designed to collect data within sites, and identified demographic information, ownership of agricultural land, involvement in key income generating activities (e.g. charcoal production, commercial crop production) and responses to the wellbeing indicators (Table 1). We conducted semi-structured interviews and trend analyses with key informants to determine village characteristics, infrastructure, resource access, distances to main markets and roads, prevalent income generating activities and historical narratives of land use. We also conducted focus group discussions: In Gurué, with soya producers to triangulate market access information from the village survey; in Marrupa, with smallholder farmers to determine the main subsistence crops grown; in Mabalane, with charcoal producers, charcoal associations and village committee members to determine a village's charcoal production history and market access (Baumert et al., 2016).

2.2.2. Geospatial data

We combined participatory mapping, GPS tagging and high-resolution google earth imagery to determine village limits. In Gurué and Marrupa, local leaders defined village limits using landscape features and by tagging physical locations of limits using a GPS. In Mabalane village limits were less rigidly defined, so instead we use a 5 km buffer around village centres (Woollen et al., 2016). We estimated woodland cover using maps of aboveground woody biomass constructed from ALOS PALSAR 2 radar backscatter data from late 2014 (Ryan et al., 2012). Woodland was defined as pixels where biomass exceeded 10 Mg C ha-1, as this threshold is suitable to distinguish woodlands from other non-wooded land cover types in an African context (McNicol et al., 2018; Ryan et al., 2012). Mapping and woodland quantification was carried out using QGIS software (v 2.18.3, 2017).

2.3. Data analysis

The data analyses comprised a three-step process. The first was the construction of a MDBW index using social data collected through the household survey, and creation of two subsequent measures of the MDWB index, including village destitution headcounts and inequality (section 2.3.1). The second was the creation of multidimensional LUI gradients for each of our three study sites, which combined social data from the household survey and geospatial data of village-level measures of aboveground woody biomass (section 2.3.2). The third process modelled the relationships between our MDWB measures and LUI gradients (section 2.3.3).

2.3.1. Multidimensional wellbeing index

We use a multidimensional concept of wellbeing, as there is a need to examine more than just income when measuring progress in development and poverty reduction (Alkire and Santos, 2013; Fisher et al., 2013; Nussbaum and Sen, 1993). We adopt the Alkire-Foster methodology for ordinal variables, which underpins the Multidimensional Poverty Index (MPI), an international measure of poverty used in the United Nations Human Development Reports (Alkire et al., 2015; Alkire and Santos, 2013). The MPI encompasses numerous indicators that reflect the multiple deprivations experienced by people across dimensions of health, living standards and education.

Wellbeing indicators were selected by triangulating participatory wealth rankings results and a structured secondary literature review (for full methodology see Vollmer et al., 2017). The MDWB index comprised 15 indicators of wellbeing, grouped across 3 dimensions (Table 1). Wellbeing indicators were counted and each dimension weighted equally. The MDWB index was normalised, ranging from 0-1, where 1 is the highest MDWB possible.

To explore the depth of destitution faced by households, our MDWB index comprises cut-off lines within each wellbeing indicator, which distinguish the poor and the destitute, as described by Alkire and Seth, (2016). Following Vollmer et al., (2017) we define a household as multidimensionally destitute (hereafter ‘destitute’) if they are considered destitute in at least 4 indicators, across at least 2 dimensions. In reference to our MDWB index, a household is considered destitute if their MDWB score is 0.7 or less. The destitution headcount denotes the percentage of the village population below this MDWB cut-off. To assess inequalities of MDWB within villages, we examined the village-level Gini coefficient of the MDWB index.

Table 1: Multidimensional wellbeing components (adapted from Alkire and Seth, 2016; Vollmer et al., 2017).

Dimension	Wellbeing indicator	A household is considered destitute if …

Human capital	Water source	All household members do not have year-round access to improved water sources, in accordance to the MDG guidelines
	Distance to water source	The time to collect water exceeds a 60 minute round trip
	Sanitation	All household members do not have access to a lavatory (e.g. defecate outside)
	Infant mortality	A child under 5 has died within the household
	Medical diagnosis	No diagnosis (from traditional or modern) was acquired for household members
	Medical treatment	No product (traditional or modern) was received for household members
	Medical affordability	No household member can afford treatment, or affords treatment with a lot of difficulty
	Child education	No child (of schooling age) has received compulsory education
	Household education	No household member has achieved post-compulsory education
Social capital	Access to services	No farmer services, credit or advice were received by any household member

	Food security	Any household member has experienced food insecurity
Economic capital	Housing material: roof	The roof is built using unimproved materials (e.g. grass roof)
	Housing material: wall	The walls are built using unimproved materials (e.g. no bricks used)
	Housing material: floor	The floor is made from unimproved materials (e.g. bare floor)
	Asset ownership	All household members own no assets (e.g. mobile phone)

2.3.2. Multidimensional land use intensity gradients

We use the conceptual framework proposed by Erb et al., (2013) to define our multidimensional LUI gradients (Please see SI.1 for the conceptual framework schematics). Erb et al., (2013) suggest “land-based production systems embedded within a territory should be at the centre of the research on land-use intensity” (p 467). Their framework integrates three dimensions: inputs to the production system (e.g. of land, labour or technology), outputs from the production system (e.g. products), and modifications to system properties and functions (e.g. to soil quality, biodiversity and carbon stocks). LUI is therefore an emergent property of a bundle of land use and landscape changes.

Understanding the temporal dynamics of ES feedbacks and trade-offs remains a challenge (Bennett et al., 2009), so in order to understand our observations in time, the LUI gradients are space-for-time substitutions that assume within each case-study area, individual study villages are on the same pathway of LUI, where individual villages each represent a different point along the space-for-time continuum. For the Gurué and Marrupa cases, we proxied chronosequence LUI gradients by constructing a linear index from the site-specific measurements of inputs, outputs and system-level modifications, using principal component analysis (Vyas and Kumaranayake, 2006) (please refer to SI.3 for the LUI measurements used in each study site, and SI.4 and SI.5 for the associated PCA results). In Mabalane we use a chronological gradient as a proxy for LUI, as described by Baumert et al., (2016) (Please refer to SI.5 for the ordinal indices for the LUI gradient). Qualitative recall data on historic changes in land use strengthened the inference from our proxy chronosequence LUI gradients.

Commercial crop production (Gurué)

LUI measurements for this site were scaled to the household, as qualitative information from the village surveys indicated that agricultural expansion was driven by households increasing their production of commercial crops, as opposed to growth in local populations. The LUI indicators focus on the intensification of the four main commercial crops in the region: soya, pulses, sunflower and sesame. Critical inputs for increased land use intensity were land (mean hectares (ha) per household (hh)) and labour (percentage of households producing commercial crops). Outputs were measured as the amount of cash generated from commercial crop production (MZN/hh). According to village narratives, households increased their production by clearing woodland, thus system alterations were attributed to the expansion of agricultural land replacing woodland, and is measured as the area of woodland per household (km^2/hh), within the village limits (please refer to SI.3 for the LUI measurements used in each study site, and SI.4 and SI.5 for the associated PCA results).

Charcoal production (Mabalane)

Each village represents different intensities of charcoal production. Inputs to the system involve labour, and some mechanisation (e.g. chainsaws). All producers use the same kiln technology, in the form of inefficient earth mounds. Charcoal is an income generating activity, therefore outputs were cash. Selective harvesting of large hardwood species (e.g. Colophospermum mopane) was the dominant production practice, as opposed to clear-cutting, thus system alterations are attributed to woodland degradation (Ndegwa et al., 2016).

Intensification of charcoal production followed a nonlinear extraction pattern: villages with longer histories of charcoal production reported that with a decline in suitable charcoal trees, large-scale operators moved to new areas for production (Baumert et al., 2016). Subsequently, inputs (labour and mechanisation) and outputs (cash) were highest in peak villages, but comparable in early and late villages. Chronologically, land use intensifies linearly (e.g. lower to higher intensification over time). However, nonlinear production systems, such as unsustainable charcoal production, create challenges when applied to Erb et al's., (2013) framework, as the framework implies linearity with increasing inputs and outputs to the production system. Therefore, rather than using input, output and system alteration measurements, we use a chronological gradient as a proxy for LUI, as described by Baumert et al., (2016) and Woollen et al., (2016) (please refer to SI.5 for the ordinal indices). The chronological proxy makes some assumptions about the LUI measurements: 1) The strength of the market influences the rate of production, whereby peak villages have the highest levels of inputs (more people producing charcoal in the village) and outputs (more income generated); 2) Villages with longer production histories have higher system alterations, as cumulatively over time more trees have been felled. A chronological gradient also circumvents some challenges with measuring charcoal-driven woodland degradation at the landscape level, as it is difficult to discern tree felling for charcoal from other woodland-resource extraction practices (e.g. harvesting of poles and firewood) (Barreda-bautista et al., 2011; Ndegwa et al., 2016).

Subsistence crop production (Marrupa)

Measurements are relative to the village level, to account for the population pressures driving agricultural expansion. Input measurements included labour (hh/km^2) and the total area of land under cultivation within the village (ha). Outputs were measured as the total amount of maize (the main staple subsistence crop) produced for consumption (kg). According to village narratives, subsistence agricultural land is created through the clearing of woodland within village limits. System alterations were thus attributed to the expansion of agricultural land replacing woodlands and measured as the woodland cover (%) within the village limits (please refer to SI.3 for the LUI measurements used in each study site, and SI.4 and SI.5 for the associated PCA results).

2.4. Statistical analyses

This research attempts to address a complex issue, which necessitates linking two distinct and multidimensional measures, operating at different levels (in this case at the village and household level). This requires relatively advanced modelling approaches, such as the Bayesian multi-level models, for analysing complex and multi-level issues (Mostafa, 2016; Green and Worden, 2015). Analysis of mixed-scale data with traditional regression or ANOVA violates the independence assumption and nested nature of our data (Burkner 2017). Hence we apply a two-step process to conduct multi-level models fitted within a Bayesian framework using Markov Chain Monte Carlo (MCMC) sampling.

MDWB was measured at the household level, whilst LUI is measured at the landscape-level. In the first step we fitted models that predict household-level wellbeing as a function of household wealth, the village in which the household was situated, and the LUI measure of that village. We used these models to post-stratify predictions of mean MDWB at the village level (i.e. predictions weighted for the observed distribution of wealth classes present in each village). This village-level average of household-level MDWB incorporates the different distributions of wealth across different villages, which may themselves be products of land-use, so is a more appropriate quantity to use to examine the relationship with LUI than household wellbeing conditional on wealth. In the second step, we therefore fitted village-level regressions of predicted mean village MDWB as a function of LUI.

We modelled household-level MDWB separately in each of the three case-study areas, fitting multilevel models with Gaussian errors. In each case, the response variable was the

MDWB index and the models included a categorical variable indicating the wealth rank of the household and one or more indices of LUI. For Gurué the model included two continuous indices of LUI derived from principal components analysis (PC1 = an index of commercialisation, PC2 = an index of agricultural expansion for commercial agriculture). For Mabalane the model used an ordinal index designed to reflect a chronological progression in the intensity of charcoal production. For the purposes of modelling, this was treated as reflecting a continuous underlying latent variable. For Marrupa the model used a continuous index of LUI derived from principal components analysis (PC1 = an index of agricultural expansion for subsistence agriculture). In all cases, the models also included random intercepts for wealth rank nested within village to account for the grouping structure of the data and the differences in the criteria used to assign wealth ranks within each village. We placed uninformative uniform priors on the beta coefficients and half-Student t priors with 3 degrees of freedom and a scale of 10 on the group-level and residual standard deviations. The models were fitted within a Bayesian framework using Markov Chain Monte Carlo (MCMC) sampling via the brms package version 2.0.0 (Bürkner, 2017) and rstan version 2.16.2 (Stan Development Team, 2018). Four MCMC chains were run in parallel for 2,000 samples each, with the first 1,000 samples in each chain discarded as warm-up. Convergence was judged by visual inspection of trace-plots and calculation of Gelman-Rubin statistics, where $r < 1.01$ was taken to indicate adequate convergence (Gelman et al., 2013).

As households were selected for inclusion in the study based on a stratified sampling scheme, with different sampling intensities within each wealth stratum we carried out poststratification to derive village-level predictions of mean MDWB, destitution headcounts and Gini coefficients (Gelman and Little, 1997). Model-based predictions were made for every household present within each of the study villages, based on the original sampling frame, and the three village-level metrics were calculated directly for each MCMC draw of these predictions. We then fitted village-level linear regression models for each metric to each of the village-level predictions to quantify their relationships to LUI, using the same indices as for the household-level models.

To quantify the association between LUI and individual components of the MDWB index (Table 1), and distances to markets, we conducted spearman's correlations. All analyses were performed in R, version 3.5.0 (R Core Team, 2018). The annotated R-code for our models can be found in the supplementary materials.

3. Results

3.1. Land use intensification processes and market access

Fig.1 shows the spatial distributions of LUI, where darker shades of grey indicate villages with higher intensifications of land use. Supplementary information (SI.5) provides individual village LUI indices (PCA scores and ordinal indices).

3.1.1. Smallholder commercial crop production

The land use narrative in Gurué was one of agricultural expansion for commercial agriculture, driven by increasing degrees of agricultural commercialisation at the household level. Principal component analysis (PCA) displayed two coexisting components. The first component (PC1) explained 66.7% of the variability, representing household transitions from lower to higher degrees of commercialisation. The second component (PC2) explained 24.8% of the variability, denoting the expansion of agriculture into forested land (Fig. S4.1). Data from village surveys and focus group discussions with soya producers indicated that villages had well-established commercial crop markets, where producers sold directly to ambulant buyers or contracted middle-men for export markets. Local markets were also numerous (three identified) and were close to all villages (ranging from 0 - 17km). We found that distance (km) to markets was correlated with PC1 (rho= 0.64 , p = 0.04), whereby villages closer to markets had higher measurable indices of LUI, but not with PC2 (rho = -0.06, p = 0.87).

3.1.2. Charcoal production

The land use narrative in Mabalane was dominated by urban-based large-scale operators, who employed migrant workers to produce charcoal. Rural households engaged in small-scale production alongside migrant producers and sold directly to the large-scale operators. Households’ access to the charcoal market was therefore closely linked to the prevalence of the large-scale producers operating in each village. Villages with longer production histories (higher LUI) indicated declines in these large-scale buyers. One village was located close to the railway line, so households also sold direct to buyers on trains bound for Maputo. Villages close to the local urban markets (< 15 km from the villages) would also sell direct to urban consumers. The distance (km) to local markets and the chronological LUI gradient were correlated (rho = 0.69, p = 0.08), whereby villages closer to markets had higher measurable indices of LUI.

3.1.3. Subsistence crop production

The land use narrative in Marrupa was one of expansion of subsistence agriculture, driven by population growth. This corresponded with the PCA results, which displayed one dominant component explaining 76.6% of the variation and characterised the expansion of subsistence agriculture, replacing forested land (Fig. S4.1). Although small amounts of commercial cropping existed in the study sites, these markets were underdeveloped. For example, nine villages were engaged in growing tobacco, of which eight villages reported restrictive issues with low sale prices and limited profits. Producers felt exploited by the low prices and lack of alternative buyers. Two villages reported producing other commercial crops, one producing vegetables (e.g. lettuce, tomato) and the other sesame. The village surveys reported that only two villages reported intra-village markets, but all villages indicated that the municipal town of Marrupa was their main market, with distances ranging between 7 - 32km. Distance (km) to Marrupa town was correlated with the PCA score (rho = 0.57, p = 0.08), indicating that villages closer to markets had higher measurable indices of LUI.

3.2. MDWB, destitution and inequality

3.2.1. Smallholder commercial crop production

Household MDWB increased with the expansion of agricultural land into forested land (PC2) (βWB-PC2 = 0.039, CI95 = 0.024, 0.055; Fig.2a), but we observed no change with household transitions from lower to higher degrees of commercialisation (PC1) (βWB-PC1 = 0.006, CI95 = -0.003, 0.015, Fig. 3a). There was no observable relationship between the prevalence of destitution within villages (destitution headcount) and transitions from lower to higher degrees of commercialisation (PC1) (βDH-PC1 = -1.825, CI95 = -4.521, 0.803, Fig. 3b), however, destitution headcounts reduced with the expansion of agricultural land into forested land (PC2) (βDH-PC2 = -9.458, CI95 = -13.249, -5.495; Fig.2b). Correspondingly, we observed no relationship between inequality and either PC1 or PC2 (βGC-PC1 = -0.001, CI95 = -0.005, 0.004; βGC-PC2 = -0.008, CI95 = -0.016, 0.000; Fig. 2c and Fig. 3c). Disaggregating individual wellbeing indicators showed that with household transitions from lower to higher degrees of commercialisation (PC1), we only observed declines in the proportion of households considered destitute in their access to services. With the expansion of agricultural land into forested land (PC2), we observed declines in the proportion of households considered destitute in five wellbeing indicators: household education, child education, roof material, water source and access to services (please see SI.6 for the correlations between the LUI rank and all wellbeing indicators).

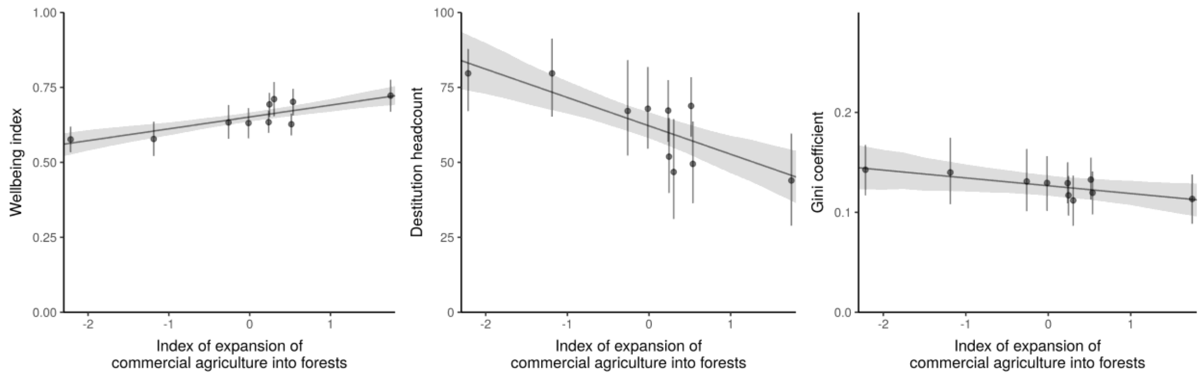

Fig.2: Trends, with increasing intensity of expanding commercial smallholder crop production in Gurué District, in a) multidimensional wellbeing, b) destitution headcounts (proportion of village that are destitute), and c) village inequality (gini coefficient).

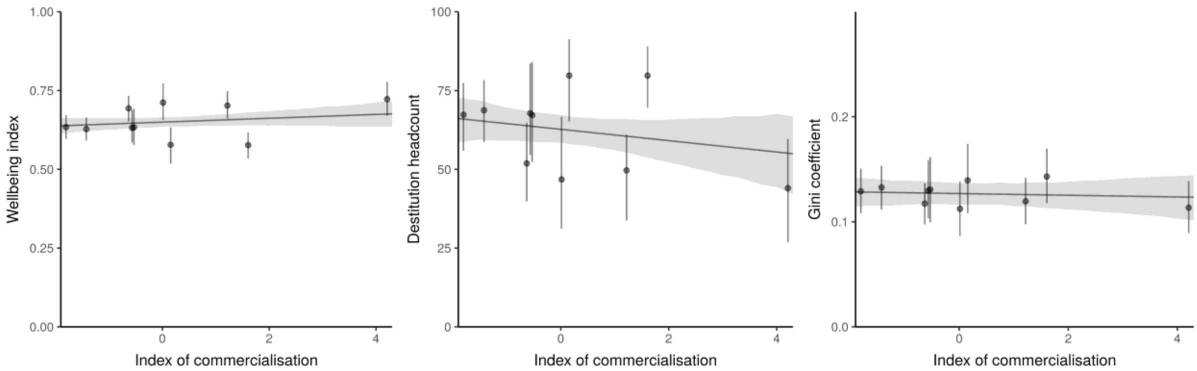

Fig.3: Trends, with increasing intensity of smallholder commercialisation in Gurué District, in a) multidimensional wellbeing, b) destitution headcounts (proportion of village that are destitute), and c) village inequality (gini coefficient).

3.2.2. Charcoal production

We found no change in the mean village MDWB index with intensification of charcoal production (βWB = -0.007, CI95 = -0.023, 0.008; Fig. 4a). Destitution headcounts did not change with intensification of charcoal production (βDH = 1.619, CI95 = -2.209, 5.665; Fig. 4b), nor did level of village inequality (βGC = 0.001, CI95 = -0.006, 0.009; Fig.4c). Disaggregating individual wellbeing indicators showed no declines in any individual wellbeing indicators, but we observed increases in the proportion of households considered destitute in their access to medical treatment (both modern and traditional) (please see SI.6 for the correlations between the LUI rank and all wellbeing indicators).

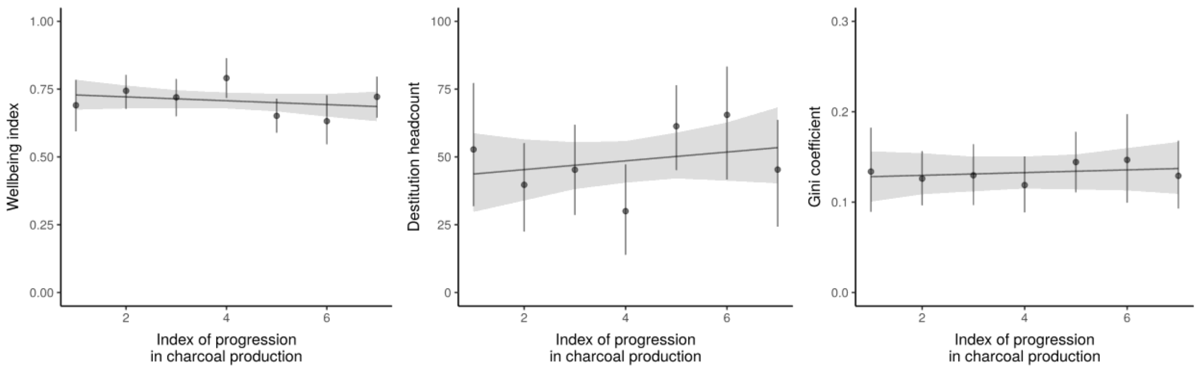

Fig. 4: Trends, with increasing intensity of charcoal production in Mablane District, in a) multidimensional wellbeing, b) destitution headcounts (proportion of village that are destitute), and c) village inequality (gini coefficient).

3.2.3. Subsistence crop production

Household MDWB increased with expansion of agricultural land into forested land (PC1) (βWB = 0.012, CI95 = -0.000, 0.023; Fig. 5a). However, we observed no clear relationships between PC1 with either destitution headcounts (βDH = -2.412, CI95 = -5.132, 0.227; Fig. 5b) or inequality (βGC = -0.003, CI95 = -0.009, 0.004; Fig. 5c). Disaggregating individual wellbeing indicators showed that the proportion of households considered destitute in terms of food security decreased with expansion of cultivation (PC1), but increased for adult education (please see SI.6 for the correlations between the LUI rank and all wellbeing indicators).

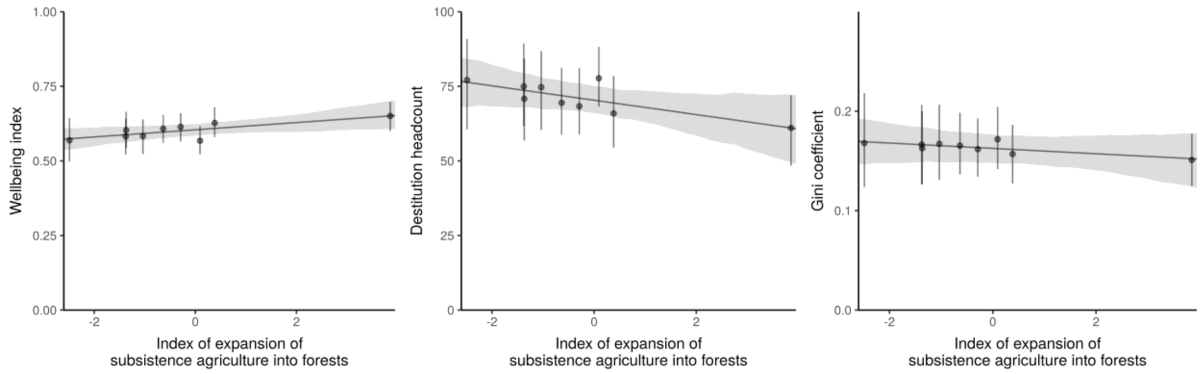

Fig. 5: Trends, with increasing intensity of expanding smallholder subsistence crop production in Marrupa District, in a) multidimensional wellbeing, b) destitution headcounts (proportion of village that are destitute), and c) village inequality (gini coefficient).

4. Discussion

We observed increases in the MDWB index with expansion of commercial and subsistence agriculture, supporting generalised claims that cropland expansion can provide a pathway for smallholder-led development across SSA (Chamberlin et al., 2014; Jayne et al., 2014). However this particular finding may depend on a number of context-specific factors, including inclusive and equitable market access and relative land abundance, both of which we examine further in our discussion. Furthermore, we found no evidence to suggest that intensification of agricultural expansion affected inequalities in MDWB, suggesting that there may have been relatively equitable access to benefits from agricultural expansion between households in each site. These findings likely reflect the low technological input and land-abundant context of Mozambique, however current trends of increasing global land scarcity means that agricultural intensification processes will require technological inputs (Chamberlin et al., 2014). Whilst the sites selected for this study were not directly affected by conflicts rising from foreign companies acquiring land rights (though see Zaehringer et al., 2018), it is impossible to rule out leakage affects, such as households opening up new land for agriculture as a result of their displacement, contributing further to land scarcity. Land scarcity typically increases income inequalities, which is increasingly pronounced in land-abundant countries such as Mozambique when local land conflicts arise from large-scale land investments (Zaehringer et al., 2018). Furthermore, agricultural intensification can exacerbate poverty and rural inequalities if social inequalities (e.g. gender, class, ethnicity) and environmental concerns are not taken into account (Ellis and Maliro, 2013; Kerr, 2012), and if land tenure remains insecure (Dawson et al., 2019).

Contributing to current debates over the poverty reduction potential of charcoal (Mwampamba et al., 2013; Schure et al., 2015; Zulu and Richardson, 2013), we observed no changes in the MDWB index, destitution headcounts or MDWB inequality with charcoal intensification. In this respect, our results provide no conclusive evidence to the contribution of charcoal to rural households, highlighting the multi-faceted livelihoods and complex socio-ecological systems in which the charcoal industry operates. That we observed no improvements in any wellbeing indicators with intensification of charcoal production, suggests that derived income may not have been invested locally. Indeed this is perhaps not surprising, as it is urban stakeholders who have been shown to benefit financially from the commercial charcoal sector (Ribot, 1998). This is a common phenomenon in countries across SSA with more formalised charcoal markets (Schure et al., 2013). In the Mabalane study area, less than 10 % of economic benefits from charcoal production are retained locally (Baumert et al., 2016). However, elsewhere in Mozambique and Malawi households invest in physical capital (e.g. improved building materials and solar panels) and human capital (e.g. purchasing medicine or transport to formal healthcare services, paying school fees) (Jones et al., 2016; Smith et al., 2017). Our findings are perhaps more indicative of limited access to derived income and of productive investments. Finally, the observed increases in the proportion of households considered destitute in their access to medical treatment may also be indicative of the loss of medicinal tree species in areas with higher LUI (Woollen et al., 2016), supporting observations that unsustainable charcoal production undermines certain ES upon which rural households rely (Chidumayo and Gumbo, 2013).

Wellbeing indicators that correlated with LUI were both endogenous, where endogeneity refers to a process that develops from within and is mediated by household agency (Bebbington, 1999; Cleaver, 2005), and exogenous (e.g. infrastructural development). These findings are indicative of the co-evolution of land use and livelihoods (Carr and McCusker, 2009), and align with understandings of the role of infrastructural development in inducing LUI (Lambin et al., 2001). Our results also corroborate existing studies, whereby agricultural intensification is associated with household food security and access to education services (Delgado, 1997; Hanjra et al., 2009; Hanjra and Gichuki, 2008). The increase in destitution for adult education with the expansion of subsistence agriculture is perhaps unexpected, and may be related to historically lower access to educational services, yet further investigation would be required for clarification.

The findings of our study suggest that increasing LUI did not equate to degradation of ES, to the point that negative impacts on human wellbeing occurred (Diamond, 2005). Rather, we find that higher rates of LUI equate to improved wellbeing, aligning with paradoxical global studies that demonstrate declines in ES are associated with gains in wellbeing (Millenium Ecosystem Assessment, 2005; Raudsepp-Hearne et al., 2010). For the observed improvements in MDWB, and perceived lack of detrimental impacts on livelihoods in our case-study sites, given the land-abundant context of Mozambique, it is also possible that levels of environmental degradation have yet to reach a tipping point in our study areas (Lenton, 2013), that wellbeing depends on improving food services, or that there are unknown and unmeasurable time-lags that may still lead to future wellbeing declines (Raudsepp-Hearne et al., 2010).

4.1. Sustainable and Inclusive Markets

Whilst we make inferences on the implications of LUI on MDWB, we acknowledge that we cannot infer causality and we recognise that LUI may not drive our observed changes, as non-ES services are essential to MDWB and livelihoods. However, as land use and these other variables co-evolve (Carr and McCusker, 2009), it is unrealistic to examine them in isolation from each other. The importance of markets for rural development and poverty reduction is well established, as is the requirement to integrate markets into our understanding of the contribution of ES to poverty alleviation (Fisher et al., 2014). Hence, we discuss our observed patterns in light of differential market access across the three sites.

The three pathways presented here have distinct markets, creating differential opportunities and outcomes for local livelihoods, particularly of the poorest. Charcoal markets across SSA, for example, are ill-defined and poorly functioning, largely due to punitive regulations and the informal and illicit nature of the sector (Doggart and Meshack, 2017; Schure et al., 2013). Without a functioning market for charcoal, resources are harvested unsustainably, forest resource degradation ensues (Ndegwa et al., 2016; Rembold et al., 2013; Woollen et al., 2016) and rural production markets shift to increasing distances from urban demand centres (Ahrends et al., 2010). In contrast, commercial agricultural markets across SSA are better supported, as their development is considered critical for economic growth across the region (The World Bank, 2009). Unlike commercial agriculture however, by definition, subsistence production has limited market dependence, as per-capita production (and consumption) remains constant, irrespective of functioning markets (Wharton, 1969).

We observed no change in destitution headcounts with LUI neither with the intensification of charcoal production nor with the expansion of subsistence cultivation. In both cases, market infrastructure was underdeveloped with access barriers (e.g. distance), and in the charcoal production site households' market integration depended on the viability of the resource base. Expansion of smallholder cultivation is particularly important for rural livelihoods and food security of the poor, when investment and market opportunities are insecure (Meyfroidt, 2018; van Vliet et al., 2012). However, our findings suggest that under circumstances of limited market access, expansion alone struggles to reduce destitution as access to functioning markets is critical to the ability of the poor to move out of poverty (Bamire and Manyong, 2003; Ellis and Freeman, 2004; Woodhouse, 2002). Access to functioning markets alongside LUI appeared integral to reducing destitution headcounts. Thus, our findings support claims that access to sustainable and inclusive markets is essential for pro-poor growth strategies (McMullen, 2011; Mitchell and Coles, 2011).

The poorest are differentially integrated into markets, due to high transaction costs and market barriers (De Janvry and Sadoulet, 2000), which may be a reason why destitution did not decrease with transitions from lower to higher degrees of crop commercialisation (PC1 in Gurué). A further explanation may also be because wealthier households have better access to, and typically benefit more from farm inputs (Ellis and Maliro, 2013). However, there is little opportunity for households to market products and consequently improve their wellbeing if infrastructure is poorly developed (Barham and Chitemi, 2009). Indeed, reduced destitution headcounts were only observed with expansion of commercial agricultural land, in the presence of better-developed market infrastructure and low cost barriers (e.g. nearby markets and internal market access within villages). Consequently, increasing local capacities is important to enhance derived benefits from improved market access (Zorrilla-Miras et al., 2018), thus equitable market access should be developed concurrently if LUI is to benefit the poorest. Additionally, the spatial distributions of LUI followed general von-Thunen pattern of expansion along transport routes (Ahrends et al., 2010; von Thünen, 1966), particularly with intensification of charcoal production and subsistence expansion, and all but one of our LUI gradients correlated with market distance.

Therefore, the spatial linkages between markets and LUI should be recognised alongside rural development pathways, reflecting the focus of development practitioners and researchers broadening into facilitating producers' market access (Shepherd, 2007).

4.2. Considering Development in Land Use Intensification

Land use intensifies in a linear fashion (e.g. from lower to higher intensification, over time), whilst the underlying complex socio-ecological processes and feedbacks are non-linear (Lambin and Meyfroidt, 2010). However, LUI research currently lacks commonly shared definitions, terminology, or approach, hindering our understanding of the underlying processes, patterns, dynamics and associated social and environmental trade-offs of LUI (Erb et al., 2013). The LUI discourse has, to-date, been centred on agricultural intensification, largely ignoring the multitude of land uses which occur within other land cover types that are also subject to intensification, such as charcoal production. Furthermore, livelihoods and human wellbeing are scarcely integrated into discussions and framings of LUI. Instead, there has been a prevailing focus on food production, where food security frames much of the discussion (Erb et al., 2013). Discussions surrounding LUI (such as the land sharing, land sparing debate) have been dichotomously framed by commodity production and biodiversity conservation, leading to calls for LUI to be framed around notions of land scarcity and commodity production to avoid conflicts that arise from a framing of food security (Fischer et al., 2014). Yet as we show in this paper, LUI and livelihoods co-evolve (Carr and McCusker, 2009), thus LUI is fundamentally a social process influenced by socioeconomic opportunities and capabilities (Erb, 2012), such as markets, which have significant and differential implications for livelihoods.

Associated trade-offs from LUI (such as social-ecological, generational or between development goals) are inevitable (Galafassi et al., 2017; Howe et al., 2014; Lotze-Campen et al., 2010; Masron and Subramaniam, 2019). The intensification of land use underpins multiple SDGs, such as SDG3: Good health and wellbeing, 6: Clean water, 7: Affordable and clean energy, 13: Climate action, and 15: Life on earth. Concurrently LUI undermines multiple SDGs. Agriculture in particular is a significant contributor to environmental degradation and climate change through, for example, its role in global land use change and associated emissions from agricultural activities and waste management (Smith et al., 2014). However, the prevalent framings of LUI, most noticeably surrounding food security, food production, land scarcity and biodiversity conservation outcomes (Erb et al., 2013; Fischer et al., 2014), have limited scope with which to examine associated trade-offs for wellbeing and livelihood outcomes, particularly when linked to ES. This is a fundamental limitation, especially in the pursuit of global development goals, as ES are not only important for the rural poor, but are fundamental to global development (Millenium Ecosystem Assessment, 2005; Teeb, 2009).

High and persistent poverty levels across SSA have focussed attention towards developing "pro-poor" strategies, reflecting concerns that inequality is rising as progress in income and productivity are primarily realised by those with higher incomes (Anderson et al., 2006; Davis et al., 2010; Dawson et al., 2016). Poverty and livelihood outcomes are often overlooked in discussions around LUI (Liao and Brown, 2018; Loos et al., 2014), yet when trade-offs are not considered in policy design, poorer people are more likely to be negatively impacted (McShane et al., 2011). Decisions on trade-offs should focus on equity, justice and fairness (Bowen et al., 2017), thus the livelihoods of the poorest should take priority (Lehmann et al., 2018) in LUI discussions and decision-making. In line with such arguments, findings from the expansion of commercial agriculture case-study exhibit conditions under which certain levels of environmental degradation, as a result of LUI, may be justifiable given the wellbeing benefits for the poor (resulting in lose-win outcomes). Importantly however, where environmental degradation does not improve the wellbeing of the poor, perhaps because derived benefits cannot be re-invested to sustain the production system or used to improve wellbeing, such as with the charcoal production case-study, incurred trade-offs are unjustifiable (resulting in lose-lose outcomes) and to be mitigated.

Alongside existing calls for explicit inclusion of livelihoods in on-going LUI debates (Liao and Brown, 2018), we argue that framings of LUI should incorporate human-environment relationships, to better reflect the realities of smallholder dominated LUI processes and effectively engage with discussions around sustainable development trade-offs. Key questions remain as to whether the value that humans derive from intensifying land-based production systems offset the often negative system level changes and outcomes so that wellbeing, particularly of the poor, can be enhanced. More research is thus required to understand the impacts of LUI on both ES and wellbeing outcomes, to obtain equitable and sustainable development whilst addressing inevitable trade-offs.

5. Conclusion

In this study, we have applied Erb et al.'s, (2013) integrative conceptual framework to create multidimensional LUI gradients. By exploring LUI through a disaggregated livelihoods lens and examining how MDWB changes with LUI, we advocate for broader research into LUI, beyond that of a dichotomous and narrow framing around food production and conservation, to reflect multi-functional and smallholder-dominated rural landscapes and critically engage with discussions around sustainable development.

We found that MDWB improved with intensification of smallholder commercial and subsistence agriculture, suggesting that the socioeconomic benefits from agricultural LUI pathways may overcome localised environmental trade-offs in the short term, under circumstances of low-input systems with relative land abundance. Under similar circumstances however, MDWB outcomes did not change with intensification of charcoal production. Our disaggregated analysis also showed that LUI had differential impacts for different groups. Only with intensification of commercial crop production, where there was higher market access, did we observe reductions in destitution headcounts. In contrast, destitution headcounts did not change in the sites with reduced market access, providing evidence that under such circumstance benefits from LUI struggle to reach the poorest. With extractive commercial woodland resources such as charcoal, sustainable resource management is key to maintaining market access, though equitable access is necessary for such resources to benefit poorer households. Hence, positive wellbeing outcomes for rural households require economic benefits to be retained locally and productive investment opportunities made available. Sustainable and inclusive markets are therefore essential developments alongside LUI to improve wellbeing for all households, to ensure that no one is left behind.

6. Supplementary information

SI.1. Conceptual frameworks for land use intensity and measurable indicators

Inputs to the production system include land, capital, labour and technology (Fig. S1.1). Outputs of the production system include products and services, and value. We define outputs in terms of products and services as this encompasses not only provisioning services, but allows for the inclusion of supporting, regulating and cultural services as outputs of the production systems (Millenium Ecosystem Assessment, 2005). Value is defined in the broadest sense to allow for multiple value types to be included, in recognition of the complexity of ecosystem service and nature valuation (De Groot et al., 2002; Pascual et al., 2012). We include value as a separate output indicator as the purpose of a production system is not only to obtain products and services, but also to generate value. Thereby, LUI in this paper can include increases in value as an intensification process (e.g. if you switch from subsistence to commercial production the service output is the same, but the value of the output may increase as a result). A production system therefore encompasses any land use from which we can derive value.

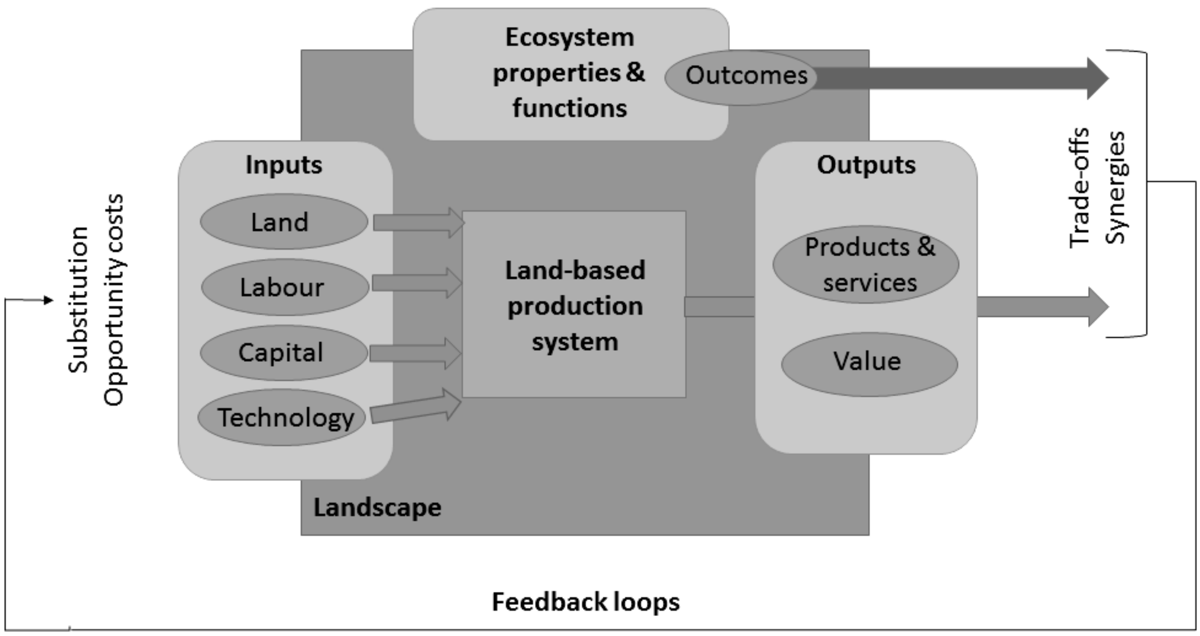

Fig. S1.1: Conceptual framework of land use intensity adapted from Erb et al., (2013). The framework schematics show the three dimensions of land use intensity and associated indicators of land base production systems, occurring within a landscape. The alterations or outcomes of changes to the system properties (i.e. ecosystem properties and functions) create trade-offs and/or synergies which feedback into the production system.

Examples of applying Erb et als., (2013) LUI framework and how it can manifest itself in our study areas can be described by four examples of LUI that smallholder farmers can pursue to increase their crop yields, or increase income from production of commercial crops. Crop yield increases can be obtained by expanding agricultural area ratios in the landscape or increasing outputs in existing agricultural fields. Cropland expansion often occurs by expansion into forest land; in land scarce situations this may manifest as expansion into less favourable areas, such as marginal land conversion or terracing. Thus within a landscape, cropland expansion is considered a form of intensification. Increasing outputs in existing agricultural areas can be obtained by increasing cropping frequencies and decreasing fallow length, requiring an increase in labour to land ratios. If agricultural technologies are available, such as mechanised tilling, irrigation or improved crops, cost to land ratios will increase. Increased income from agriculture can be obtained by producing more commercial crops either through increasing yields of existing commercial crops, or by swapping subsistence crops for commercial crops. Each of these approaches causes changes to the system properties within the landscape that they occur, such as land cover, water quality and quantity, carbon cycling, soil condition and biodiversity, and can have varied trade-offs and synergies.

SI.2. Village selection criteria

Table S.2.1: Village characteristics used to determine the village selection criteria

Village structure	Foundation year, population (number of households), number of satellite villages
Access	Road type, main market accessed, type of vehicular access
Migration	Post-war migration, current migration
Land	Ownership of secure land rights: *Direito do Uso e Aproveitamento da Terra* (DUAT)
Water	Type and number of potable water sources available
Education	Number of school, highest education levels, attendance rates
Health care	Main health issues in the village, type of health centres available
Livelihood activities	Dominant livelihood activities in the village, year activity started

SI.3. Land use intensification measurements used in each study site

Table S3.1: Summary of LUI measurements used in the principal component analysis, and data collection methods used.

LUI	Dimension type	Indicator	Data collection method
Smallholder commercial crop production (n = 10)	Input	Proportion of the village producing commercial crops (% of households (hh))	Household survey
		Mean area of land under cultivation (ha/hh)	Household survey
	Output	Total cash outputs from commercial crops (MZN/hh)	Household survey
	System property	Area of woodland per household (km^2/hh)	Biomass maps, village limits and household list
Subsistence crop production (n = 10)	Input	Population density within village limits (hh/km^2)	Household list and village limits
		Total land under cultivation (ha)	Household survey
	Output	Total maize produced for consumption (kg)	Household survey

	System property	Woodland cover within village limits (%)	Biomass maps and village limits

SI.4. Principal component analysis outputs for village land use intensification indicators in Gurué and Marrupa.

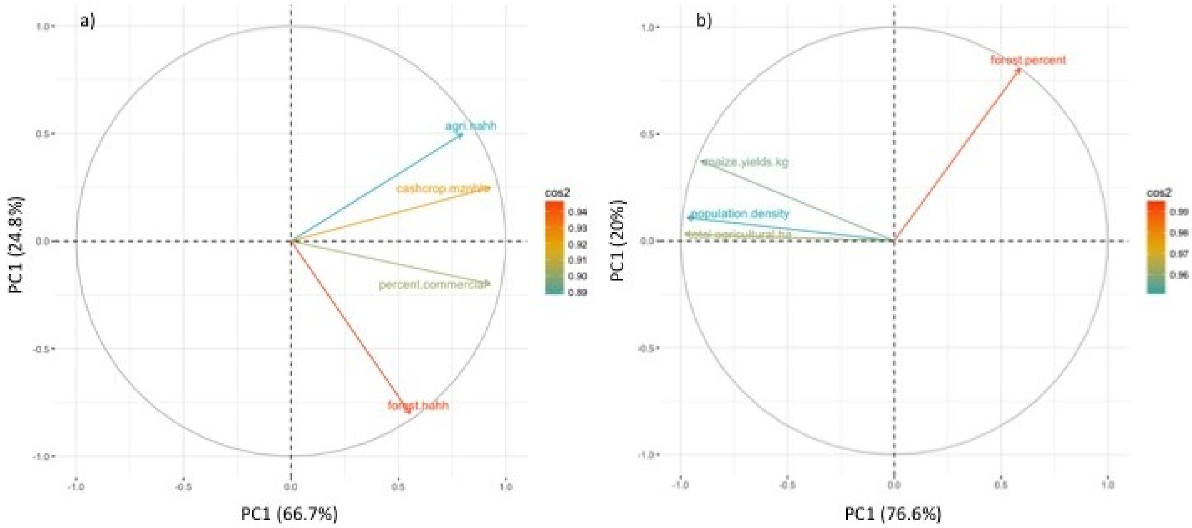

Fig. S4.1: Variable correlations plots of the principal component analysis outputs for land use intensification measurements. In a) Gurué, PCA1 denotes household transitions from lower to higher degrees of commercialisation, PC2 denotes the expansion of agricultural land, replacing forested land. In b) Marrupa, PCA1 denotes the expansion of subsistence agriculture, replacing forested land.

SI.5. Village-level wellbeing data and land use intensification measurements (PCA scores and ordinal indices).

Table S5.1: Village-level wellbeing data and land use intensification measurements (PCA scores and ordinal indices).

District	Village MDWB index	Destitution headcount (%)	Gini coefficient	Household transitions from lower to higher degrees of commercialisation (low = -1.80)	Expansion of commercial agriculture into forested land (low = -2.22)*	Ordinal charcoal sequence (low = 1)	Expansion of subsistence agriculture, replacing forested land (low = 2.49)**
Gurue	0.59	92.09	0.11	1.61	-2.22	-	-
	0.58	95.14	0.11	0.16	-1.19	-	-
	0.64	71.21	0.15	-0.53	-0.26	-	-
	0.63	74.61	0.11	-0.57	-0.01	-	-
	0.64	68.99	0.12	-1.80	0.24	-	-
	0.70	55.90	0.10	-0.63	0.25	-	-
	0.72	50.02	0.10	0.01	0.30	-	-
	0.62	70.59	0.15	-1.42	0.52	-	-

	0.71	46.98	0.14	1.22	0.54	-	-
	0.71	43.02	0.10	4.21	1.75	-	-
Mabalane	0.68	57.89	0.17	-	-	1.00	-
	0.75	47.91	0.11	-	-	2.00	-
	0.72	57.23	0.11	-	-	3.00	-
	0.80	27.78	0.12	-	-	4.00	-
	0.64	65.10	0.15	-	-	5.00	-
	0.61	76.67	0.15	-	-	6.00	-
	0.72	39.65	0.13	-	-	7.00	-
Marrupa	0.58	79.72	0.12	-	-	-	2.49
	0.77	51.71	0.12	-	-	-	1.51
	0.56	84.51	0.17	-	-	-	1.38
	0.60	73.74	0.17	-	-	-	1.37
	0.59	75.84	0.17	-	-	-	1.04

	0.61	70.66	0.18	-	-	-	0.64
	0.61	66.96	0.16	-	-	-	0.29
	0.56	85.27	0.15	-	-	-	-0.09
	0.66	69.50	0.15	-	-	-	-0.38
	0.68	59.60	0.14	-	-	-	-3.85

For the expansion of commercial agriculture a lower PCA score (min = -2.22) indicates a lower level of LUI. For this particular system, fewer inputs equate to fewer people producing commercial crops, and less land under cultivation, fewer outputs equate to less cash generated from cash crops, and fewer changes to the system properties equate to higher forest cover. A higher PCA score (max = 1.75) indicates a higher level of LUI. For this system, higher inputs equates to more people producing commercial crops, and more land under cultivation, higher outputs equate to more cash generated from cash crops and more changes to the system properties equate to lower forest cover.

For the expansion of subsistence agriculture, a lower PCA score (min = -3.85) indicates a higher level of LUI. For this particular system, higher inputs equate to higher population densities and more land under cultivation, higher outputs equate to more maize being produced, and more changes to the system properties equate to lower forest cover. A higher PCA score (max = 2.49) indicates a lower level of LUI. For this system, fewer inputs equate to lower population densities and less land under cultivation, fewer outputs equate to less maize being produced, and fewer changes to the system properties equate to higher forest cover. In Fig.6 we reversed the PCA scores for model fitting and plotting, so that negative PCA scores correspond to lower LUI.

SI.6. Spearman correlation between LUI and the proportion of households within villages considered destitute in individual wellbeing indicator

Table S6.1: Spearman correlation between LUI and the proportion of households within villages considered destitute in individual wellbeing indicator

Wellbeing indicator	Commercial crop production (Gurué)		Charcoal production (Mabalane)		Subsistence crop production (Marrupa)	
	rho	p-value	rho	p-value	rho	p-value
Water source	-0.498	0.14	0.033	0.94	-0.017	0.97
Distance to water source	-0.345	0.33	-0.314	0.56	0.527	0.14
Sanitation	-0.644	0.04	-0.429	0.41	-0.3	0.92
Infant mortality	0.316	0.37	-0.383	0.45	-0.05	0.91
Medical diagnosis	0.067	0.85	0	1	0.44	0.235
Medical treatment	-0.434	0.21	-0.131	0.8	0.099	0.79
Medical affordability	-0.675	0.03	0.2	0.71	-0.226	0.56
Child education	-0.783	0.007	-0.522	0.28	0.084	0.83
Household education	-0.89	0.0005	-0.696	0.12	0.782	0.01

Access to services	-0.539	0.11	0.086	0.91	-0.025	0.95
Food security	0.024	0.94	0.086	0.92	-0.883	0.003
Housing material: roof	-0.705	0.02	0.143	0.8	-0.114	0.77
Housing material: wall	-0.628	0.05	0.377	0.46	-0.612	0.08
Housing material: floor	-0.207	0.56	-0.371	0.49	0	1
Asset ownership	-0.158	0.66	-0.638	0.17	0.125	0.75

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